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What is the effective luminance or effective area of non-uniform LED-luminaires in discomfort glare rating with UGR?

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Was ist die effektive Leuchtdichte oder effektive Fläche von strukturierten LED-Leuchten bei der Blendungsbewertung mit UGR?

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Problemstellung und Forschungsfragen

In der Innenbeleuchtung hat sich das Unified Glare Rating Verfahren (UGR-Verfahren) zur Bewertung der psychologischen Blendung durchgesetzt. Strukturierte LED-Leuchten können jedoch nicht mit dem UGR-Verfahren bewertet werden, da sich die Bestimmung der leuchtenden Fläche in der Praxis schwierig gestaltet.

Stand der Wissenschaft/Technik

Die CIE-Schrift 117 zum UGR-Verfahren schlägt verschiedene feste Leuchtdichteschwellen zur Bestimmung der leuchtenden Fläche von Leuchtstofflampenleuchten vor. Ebenfalls für derartige Leuchten wurde von WOLF [vgl. LiTG-Publikation 20:2003; Dissertation S. Wolf 2004] ein adaptives Verfahren basierend auf der Leuchtdichteverteilung im Raum vorgeschlagen. Für LED-Leuchten existiert bisher keine Schwellendefinition. Von HARA [Hara auf CIE-Tagung 2015] wurden für LED-Leuchten ein Korrekturfaktor zur Bestimmung der effektiven Leuchtdichte vorgestellt. Das empirische Modell dafür muss noch validiert werden.

Forschungshypothesen

- Zur Berechnung der effektiv leuchtenden Fläche bei LED-Leuchten muss das Leuchtdichtebild der Auflösung des Auges und der rezeptiven Felder angepasst werden, da die „wahrgenommene“ Auflösung bei Blendung durch LEDs eine wichtige Rolle spielt.
- Der Korrekturfaktor nach HARA und das optimierte Verfahren zur Bestimmung der leuchtenden Fläche sind geeignet zur Blendungsbewertung von LED-Leuchten in Innenräumen.

Versuchsaufbau

Die Versuche fanden in einem büroähnlichen Raum mit einer variablen Blendquelle statt (vgl. [Funke auf Licht 2014 und CIE-Tagung 2015]). Dabei beurteilten jeweils 30 Probanden die psychologische Blendung bei verschiedenen Hintergrundleuchtdichten (42-190 cd/m²), Blendwinkeln (0° bis 30°) und Leuchtdichtestrukturen (L_{max}/L_{min} = 1 bis 1000). Insgesamt wurden 19170 Blendurteile abgegeben.

Ergebnisse im Vergleich mit bisherigen Ergebnissen

Im Wesentlichen konnten die beiden Forschungshypothesen bestätigt werden. Darüber hinaus konnte in Übereinstimmung mit anderen Wissenschaftlern festgestellt werden, dass die Leuchtdichtestruktur zwar bereits bei 30° Blendwinkel einen (geringen) Einfluss auf das Störempfinden hat, besonders deutlich wird der Effekt aber erst bei 0°. Weiterhin wurde festgestellt, dass der Abstand der LEDs keinen Einfluss auf das Blendempfinden hat.

What is the effective luminance or effective area of non-uniform LED luminaires for discomfort glare rating with UGR?

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Research issue

In indoor lighting, the Unified Glare Rating (UGR) has been standardized for the assessment of discomfort glare. In fact, non-uniform LED luminaires cannot be rated with UGR as it is difficult to determine the luminous area in practice.

State of science/technology

In CIE report 117 on UGR, several fixed luminance thresholds for the determination of the luminous area of fluorescent lamps are suggested. Alternatively, an adaptive method for the estimation of luminance thresholds based on the luminance distribution in the room was proposed by WOLF [see LiTG publication 20:2003; Dissertation S. Wolf 2004]. In contrast, for non-uniform LED luminaires, a defined luminance threshold does not exist. However, HARA [Hara on CIE conference 2015] presented a correction factor model to calculate the effective luminance of non-uniform LED luminaires. In fact, the underlying empirical model still needs to be validated.

Research hypotheses

- In order to calculate the effective luminous area of LED luminaires, the luminance picture has to be adapted due to the resolution of the eye and the receptive fields, because the 'perceived' resolution has an important impact on discomfort glare.
- The correction factor according to HARA and the optimised procedure for the determination of the luminous area are both suitable for discomfort glare rating of LED luminaires in indoor environments.

Experimental setup

The experiments were conducted in an office-like room with a variable glare source (see [Funke at Licht 2014 and CIE conference 2015]). Within the tests, 30 subjects rated discomfort glare at various background luminances (42 to 190 cd/m²), glare angles (0° to 30°) and luminous patterns (L_{max}/L_{min} = 1 to 1000). All in all, 19,170 glare assessments has been taken.

Results in comparison with previous findings

Basically, both research hypotheses could be verified. Moreover, in agreement with other scientists, we observed, that the luminous pattern already had a (small) impact on perceived glare, but the effect was considerably high at direct view into the luminaire. Furthermore, the distance of LEDs inside the luminaire had no significant effect on discomfort glare in this study.

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Abstract

Since LED light spots usually are smaller than 0.0003 sr for typical indoor distances, luminaires with visible LED cannot be rated with Unified Glare Rating (UGR). In order to determine the impact of the luminous structure of the glare source on the subjective discomfort appraisal, we conducted a psychometric study. In this study it could be found that the luminous structure of non-uniform luminaires has an impact on the subjective discomfort appraisal. Especially the luminance of the relatively dark parts of the luminaire affects the subjective discomfort assessment and the average luminance of the glare source. Basically, both the effective luminous area and the effective luminance method are suitable to assess discomfort glare of non-uniform LED luminaires.

1 Introduction

In indoor lighting applications the UGR method has been standardised for the assessment of discomfort glare. It has been developed for glare source sizes ranging from 0.0003 sr to 0.1 sr [1]. In the UGR formula (1), the main impacts on discomfort are the number of glare sources n, the average luminance of glare sources L_s, the projected solid angle of the glare source Ω_s, the position index P and the background luminance L_b.

$$UGR = 8 \cdot lg\left[\frac{0{,}25}{L_b} \cdot \sum_{i=1}^{n} \frac{L_s^2 \cdot \Omega_s}{P^2}\right] \quad (1)$$

However, luminaires with visible LEDs cannot be rated with UGR. For non-uniform luminaires it is difficult to define the average luminance and the projected solid angle of the glare source. Is it possible to average the whole geometric surface of the luminaire or do only the LED light spots have to be taken into account? If only the LED light spots are assessed as the glare source, the resulting UGR value strongly depends on the resolution of the measuring device. Besides, since LED light sources are very small and have high luminance levels, a variation of the effective glare spot size results in different values of "$L_s^2 \cdot \Omega_s$" and therefore different UGR values.

2 Investigation method

In order to determine the impact of the luminous structure of the glare source on the subjective discomfort appraisal, we conducted a psychometric study based on the following research hypotheses:

- In order to calculate the effective luminous area of LED luminaires, the luminance picture has to be adapted due to the resolution of the eye and the receptive fields, because the ‘perceived’ resolution has an important impact on discomfort glare.

- The correction factor according to HARA and the optimised procedure for the determination of the luminous area are both suitable for discomfort glare rating of LED luminaires in indoor environments.

For this study, we designed a full-scale test room with a 0.6 m x 0.6 m recessed glare source in the ceiling, which could be varied in the luminance and the luminous flux of the visible LED, the number and distance of the visible LED, the luminance of the immediate vicinity of the LED and the size of the homogeneous lighting immediate vicinity. For the variation of the aspects above we have chosen a layout, which was adapted from Eberbach [2] (see figure 1). By comparing the results of series 1 and 2, it is possible to test the summation of LED light sources for discomfort glare. Pattern number 5 represents the uniform glare source at different luminance levels. The comparison of the results within series 3 shows the impact of the LED spot distance inside a luminaire. By means of the fourth series the influence of the homogeneous lighting immediate vicinity shall be investigated.

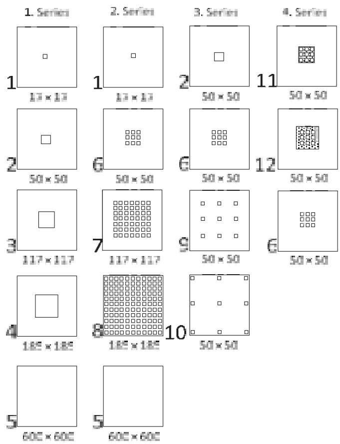

Figure 1: Luminance patterns of the glare source, sorted in four series. The shaded areas represent the “darker” parts and the white ones the “bright” parts of the glare source.

The study was conducted in an office-like test room (see figure 2), which was equipped colour-neutral. In the ceiling of the room the variable glare source was installed. Additionally, nine ambient light sources were installed in order to maintain a fixed ambient luminance when the glare source was varied. All luminaires had a correlated colour temperature between 4000 K and 4500 K. Each of the twelve patterns (see figure 1) was presented with various luminances for the “bright” and the “dark” parts of the glare source, altogether 71 light situations. Each light situation was presented at seven different tasks and viewing directions (see figure 2 and table 1). The main visual task during the test was a concentration performance test (CPT), which was presented on a computer screen in front of the subject. In addition to the visual CPT, an aural CPT was done. After 15 seconds to complete the task, the subject stated the calculation result and his discomfort glare rating. In order to consider the task difficulty, also an easy task (point fixation) was presented. Task 1 and task 4 were repeated once after six months to check the repeatability of the glare estimations. The subjective discomfort assessment was done by the multiple criterion Söllner scale. In total 19,170 glare assessments have been performed.

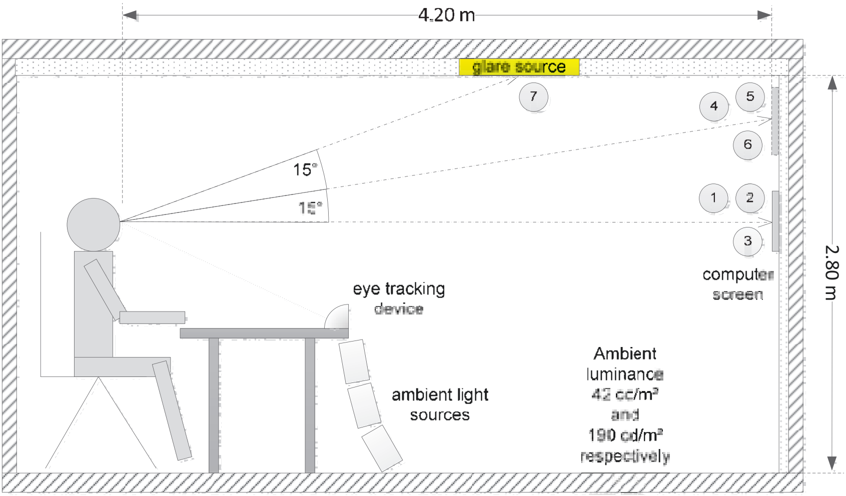

Figure 3: Position of the test person in the test room. The numbers 1 to 7 represent different tasks and viewing directions.

Each task was performed by 30 subjects (13 women, 17 men). Therefrom four were employees of the lighting engineering group at the TU Ilmenau. The other 26 subjects had no experience in lighting and were aged between 20 and 33 years (mean: 25.1 years). All test persons had a minimum visual acuity of 0.6 for near and far distances. Eight subjects used contact lenses during the test.

Table 1: List of tasks, viewing directions and ambient luminances

Task number	**Task**	**time for task**	**θ (angle to glare source)**	**Background luminance L_b**
1	CPT	15 s	30°	42 cd/m²
2	CPT	15 s	30°	190 cd/m²
3	Aural CPT	15 s	free view	42 cd/m²
4	CPT	15 s	15°	42 cd/m²
5	CPT	15 s	15°	190 cd/m²
6	Point fixation	7 s	15°	42 cd/m²
7	Short gaze in glare source	7 s	0°	42 cd/m²

3 Results

In previous publications from the authors [3; 4] it was shown, that the LED pitch has no influence on discomfort glare and that the luminous area of LEDs can be aggregated by means of glare perception. This was observed for all of the investigated viewing angles, tasks and background luminances. On the other hand, the surrounding background of the LED luminaire has a negative influence on discomfort glare ratings even at low luminance levels. In this study, we would like to present two possible methods to handle non-uniformity of glare sources: the **effective luminous area** and the **effective luminance**. The first method is an improvement of the luminous element detection procedure published in [4]. In the second method, instead of ascertaining the effective glare source size, the effective luminance is estimated by correcting the average luminance of the glare source. This approach is mainly promoted by HARA [5; 6].

3.1 Determination of effective luminous area of the glare source

The CIE report no. 117 [1, p. 25ff.] proposes different methods to determine the luminous part of the luminaire. For example, in fluorescent lamps' applications, if the luminance of a luminous element is higher than 500 cd/m², the element is considered as a glare source. For non-uniform LED luminaires, there is no information provided. In our study, we tested the 500 cd/m² definition above as well as the luminous element detection method proposed by WOLF [7]. He calculates an adaptive luminance threshold from all luminance pixels inside a room in order to determine the luminous parts of the luminaire. In the present study, we measured the luminance distribution from the subject's position with two imaging luminance measurement devices (ILMD), both with a resolution of 1.3 megapixel, but one equipped with fisheye lens and the other with 25-mm-lens, in order to get a high resolution of the glare source luminance values (see figure 4 and 5).

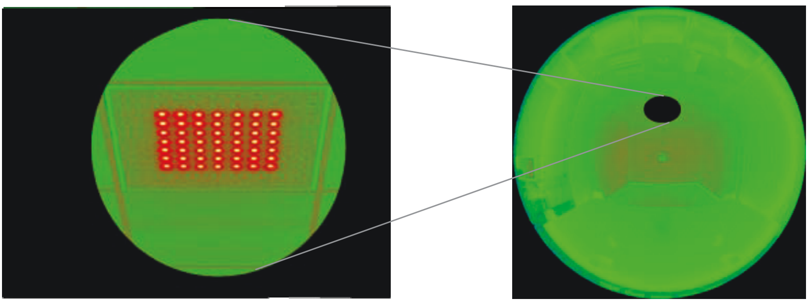

Figure 4: Luminance picture of glare source

Figure 5: Luminance picture of test room

In addition to [4], before calculating luminance thresholds or UGR values, we transformed the high resolution image of the glare source into the 'appropriate' resolution. This resolution should be according to the resolution of the eye from the observer's position and at the observer's viewing angle. This means, that the appropriate resolution changes, if the subject is looking into another direction. Therefore, the highly resolved luminance picture of the glare source (e.g. figure 4, resolution: 0,014 °/px, or 6,6*10^{-8} °/sr respectively) needs to be downscaled correspondingly. The downscaling process was done in three steps:

1. Downscaling the picture resolution according to the visual acuity of the human eye at the relevant viewing angle of the observer [8]

2. Cutting the very high luminance values according to cone saturation of the human eye due to adaption mechanisms [9]
3. Downscaling the picture resolution according to size of the perceptive fields (= size of receptive fields) of the human eye at the relevant viewing angle of the observer [10]

After downscaling the highly resolved luminance picture, the luminance thresholds according to [7] can be calculated and the luminous parts of the luminaire can be identified. Alternatively, the fixed luminance threshold of 500 cd/m² can be used to determine the luminous elements of the glare source. Subsequently, the UGR values of the contiguous 'glaring' pixels can be calculated and finally aggregated into the UGR value of the whole luminaire. In our study, both the fixed and the adaptive luminance threshold method generated UGR values which correlated very well with the subjective glare assessments (R^2 always greater than 0.9).

3.2 Determination of effective luminance of the glare source

In order to estimate the actual luminance, HARA proposed a correction factor, which is multiplied with the average luminance of the glare source [5, 6]. This correction factor can be calculated using the 'uniformity' of the glare source, which is defined as the average luminance of glare source divided by the maximum pixel value of the glare source from perpendicular view [6]. The correction factor is calculated using equation (2) [6]. Of course, for uniform glare sources, the correction factor is equal to one.

$$k = 10^{-0{,}15 \cdot \lg U} = U^{-0{,}15} \tag{2}$$

In our study we compared the theoretical correction factor with the 'subjective' correction factor, which can be derived from the psychometric glare assessments of lighting situations with a uniform glare source. Figure 6 suggests, that the correction factor model using equation (2) is good to describe discomfort glare, especially when the subject looks directly into the glare source (green squares). If the glare source is in the periphery of the subjects visual field, the calculated UGR values tend to be too critical.

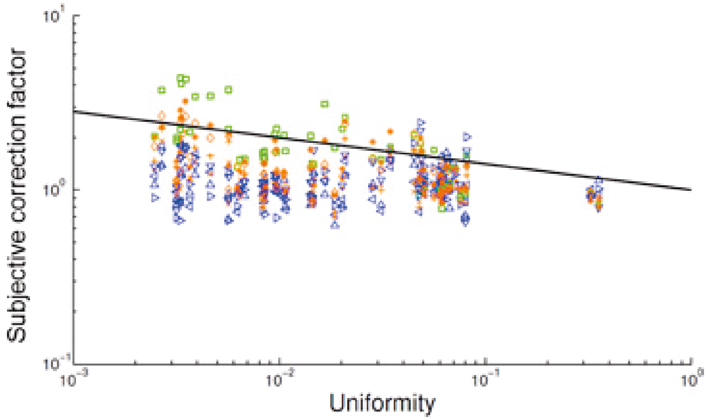

Figure 6: Subjective correction factor versus calculated uniformity. The black descending line represents the theoretical values according to equation (2).

4 Discussion

All in all, both research hypotheses could be verified. The effective luminous area method, described in this paper, appears be appropriate to assess discomfort glare indoor environments, because the best-fit lines are very close and have very high coefficients of determination ($R^2 > 0.9$). On the one hand, this method is adapted from physiological properties of the human eye, which makes it suitable to describe the ‘perceived’ resolution of the eye. On the other hand, it is still quite complicate to use and may be simplified a bit in the future for practical applications. In contrast, the correction factor according to HARA is very easy to use but it is still a bit too critical for most lighting applications. Eventually, for this procedure the ‘appropriate’ resolution of the glare source still needs to be defined.

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